Unraveling the transverse structure of nucleons with p+He-3 and e+He-3

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Workshop on opportunities for polarized He-3 in RHIC and EIC
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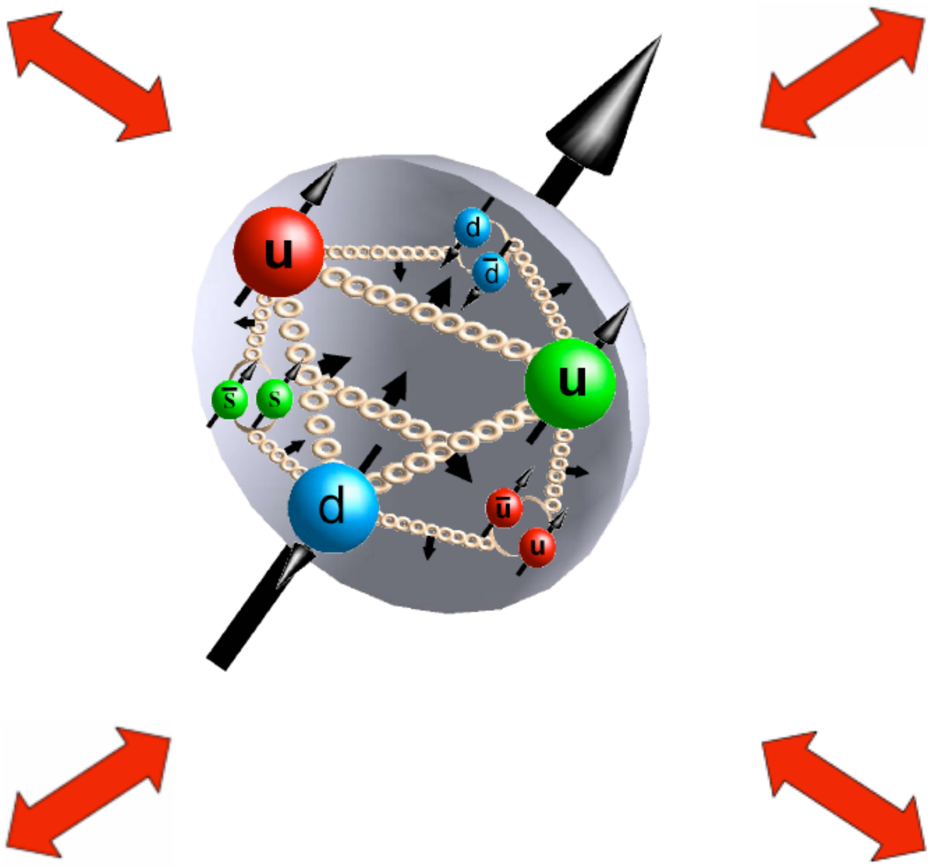
Outline

- Introduction
  - 3D structure of the hadron
  - spin as a tool to probe transverse motion
- Single spin asymmetries at RHIC
  - single inclusive hadron production: p-p, p-n, p-He3
  - Drell-Yan production: p-p, p-n, p-He3
- Sivers effect at EIC
  - e-p, e-n, e-He3
- Summary

Exploring the nucleon: of fundamental importance in science

Know what we are made of:
Most abundant particles around us
Building blocks of all elements

Fundamental properties:
Proton mass, spin, magnetic moment, understand them in terms of the internal degrees of freedom

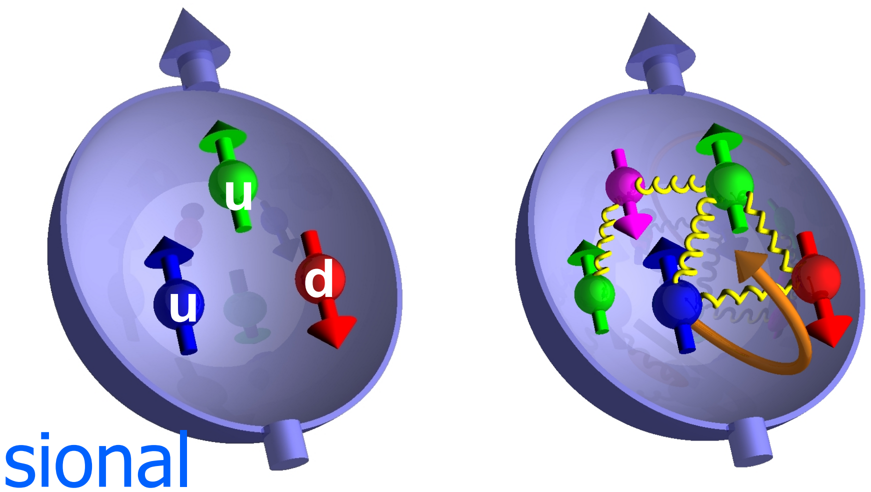


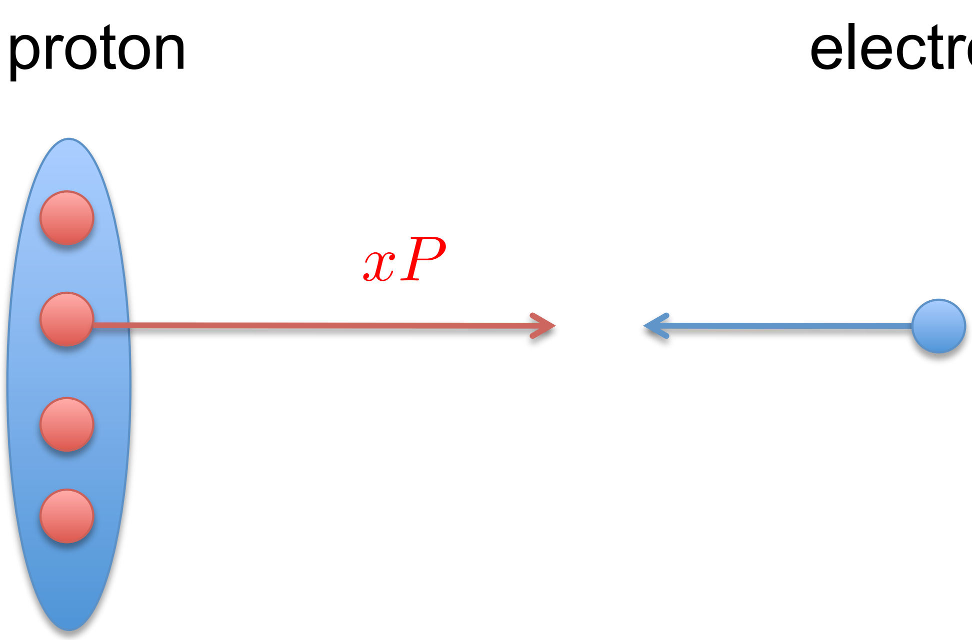
Tool for discovery:
Colliding high energy nucleons
New Physics beyond SM
LHC, Tevatron, RHIC, HERA, ...

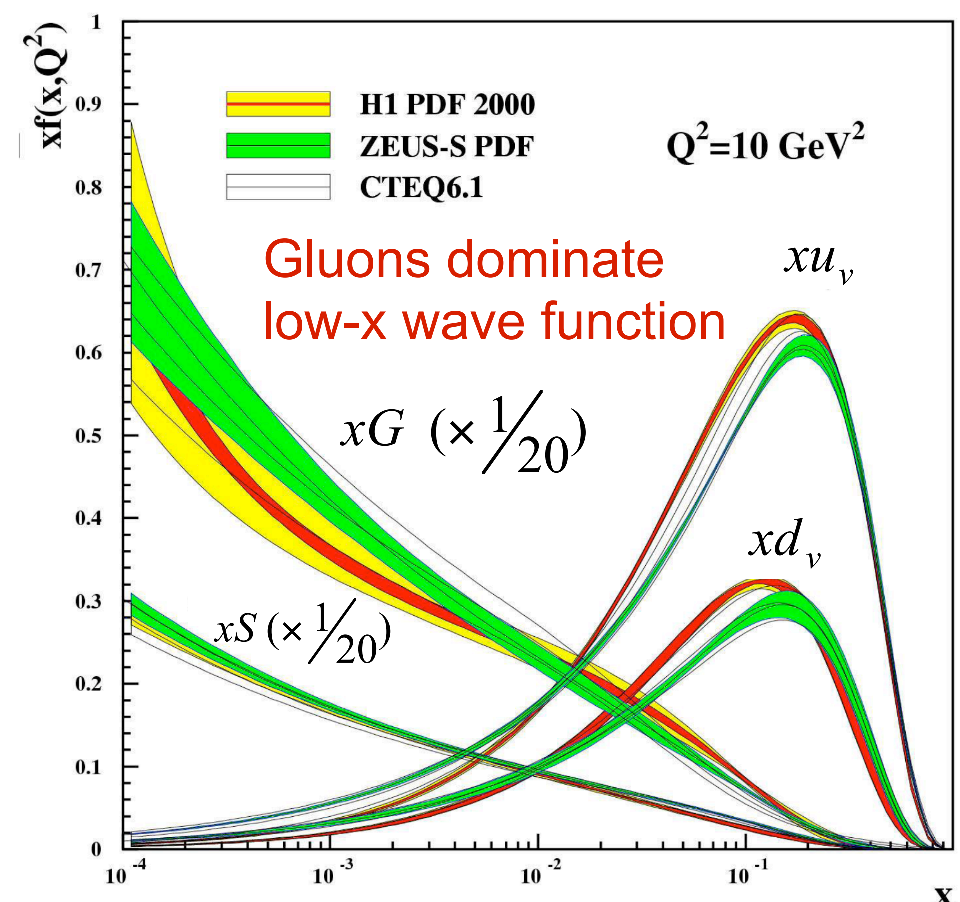
Exploring QCD and strong interaction:
Confinement, Lattice QCD, Asymptotic freedom, perturbative QCD, ...

Hadron structure

- Proton is made of
  - 2 up quarks + 1 down quarks
  - + any number of quark-antiquark pairs
  - + any number of gluons
- So far the picture is more or less one-dimensional

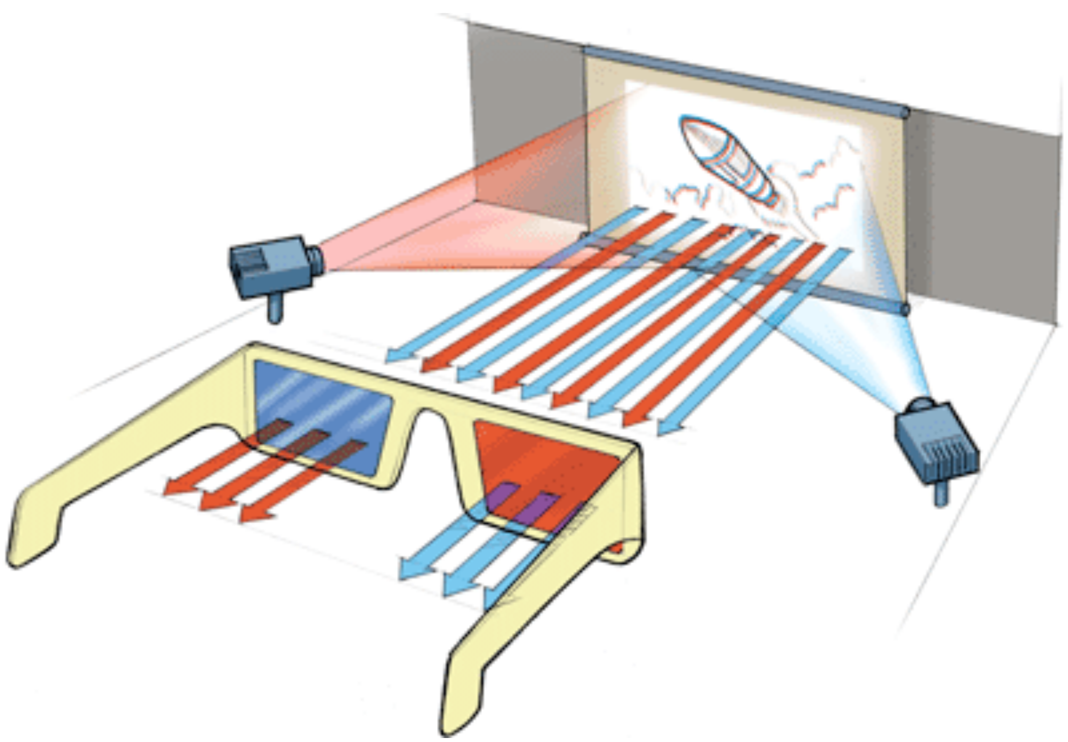






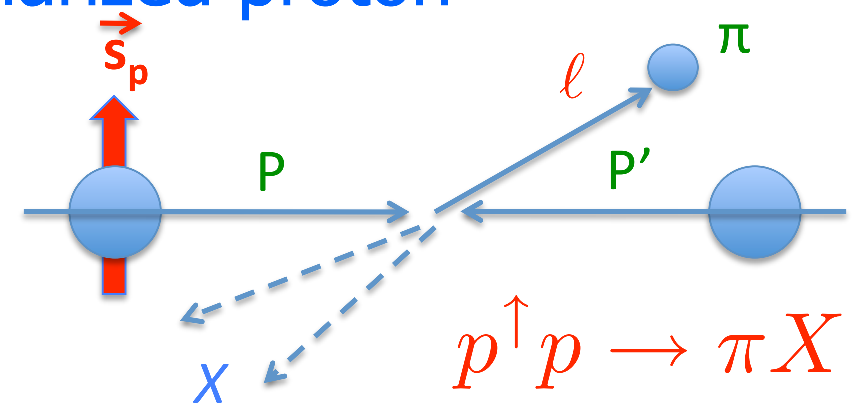
What about transverse motion?

- Uncertainty principle tells us that parton also carries transverse momentum $\langle k_\perp \rangle \sim \Lambda_{\mathrm{QCD}}$
  - How do they move in the transverse plane?
  - Do they orbit, and carry orbital angular momentum?
  - moving from 1-dimension to 3-dimension



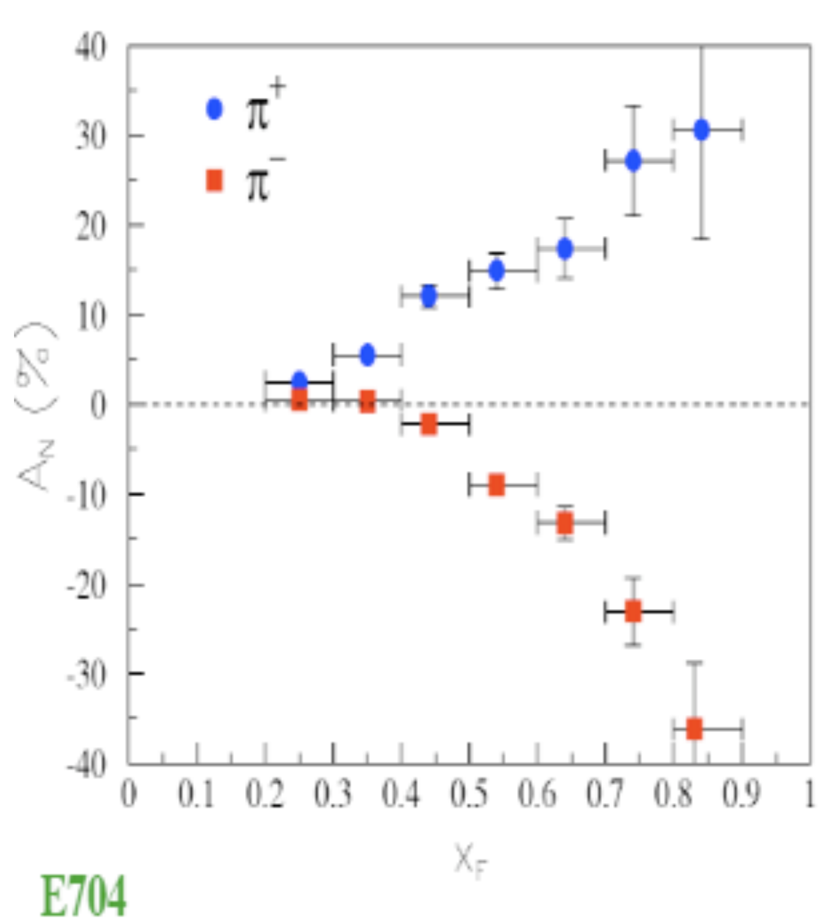
Single transverse spin asymmetry (SSA)

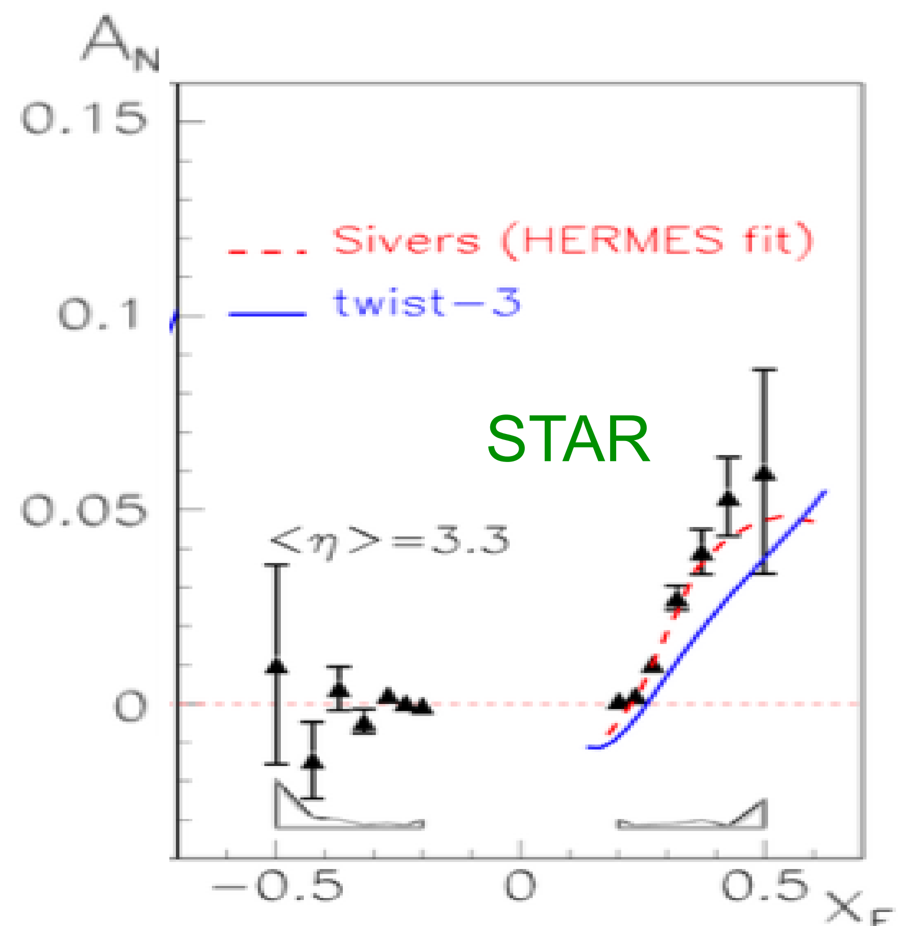
- Consider a transversely polarized proton scatters with another unpolarized proton



$$p^{\uparrow}p \to \pi X$$

$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})}$$





PHENIX
HERMES
COMPASS
JLAB, too

SSA vanishes at leading twist in collinear factorization

Kane, Pumplin, Repko, 1978

- If partons are collinear (without transverse motion)

$$A_N \sim \alpha_s \frac{m_q}{P_T} \rightarrow 0$$

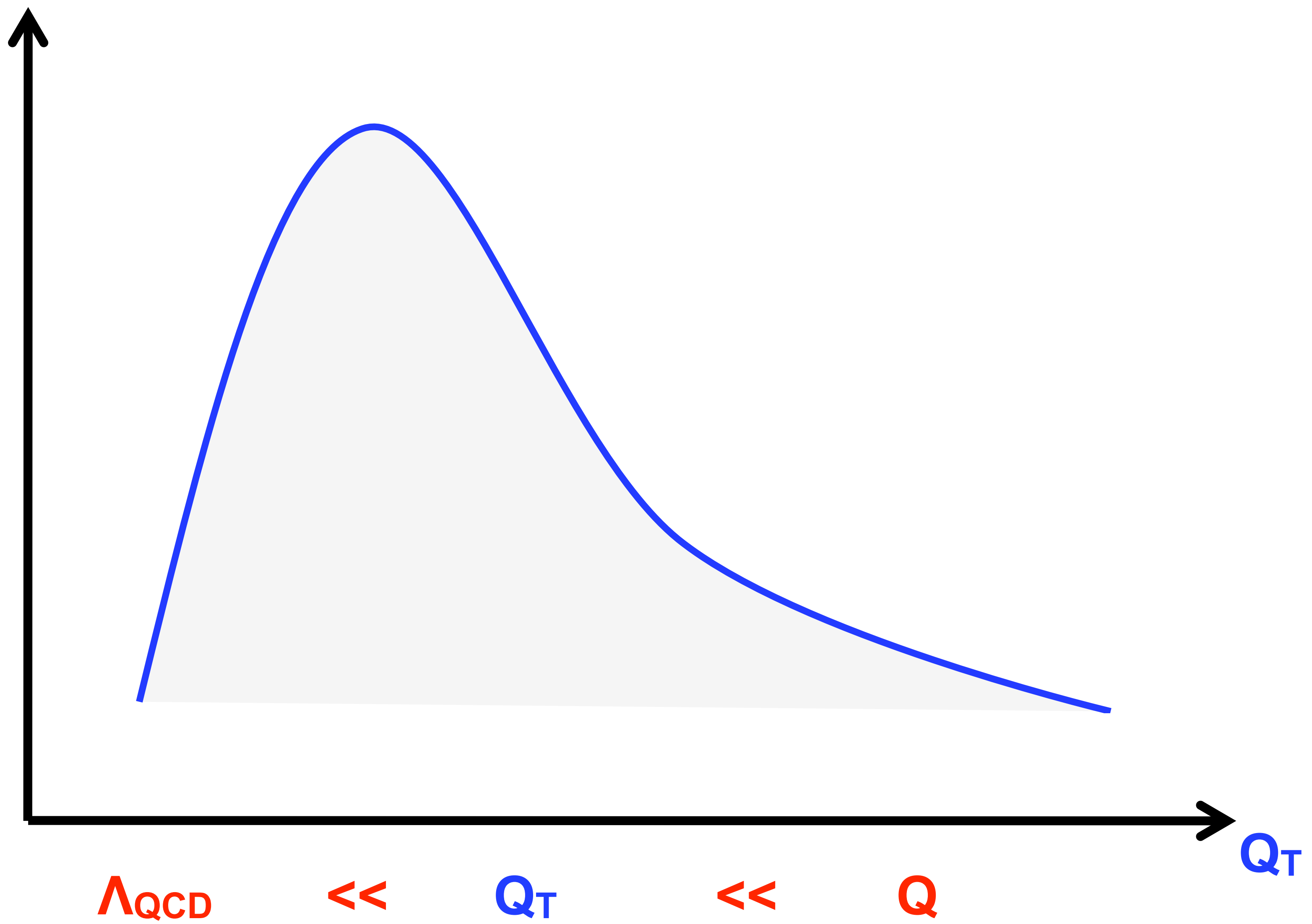
- $A_N \neq 0$: result of parton's transverse motion

- With transverse spin, one could then have many interesting correlation, which correlates spin and the transverse momentum of the parton. In other words, spin here is a useful tool to study parton's transverse motion.
  - In the incoming nucleon, there are 8 TMDs
  - For the outgoing produced pion, there are 2 TMDs

Two ways to contain transverse momentum

- One could immediately think of two ways to contain the parton transverse momentum
  - Generalize the collinear distribution f(x) to f(x, kt)
  - Taylor expansion: $f(x, kt) = f(x) + kt * f'(x) + ...$, where $f'(x)=df(x,kt)/dkt$ at $kt=0$. Then $\int d^2kt\, kt\, f'(x)$ = a higher-twist correlation
- The first approach is called TMD approach (transverse-momentum-dependent distribution)
- The second approach is called collinear twist-3 approach

A unified picture for Drell-Yan (leading Q_T/Q)



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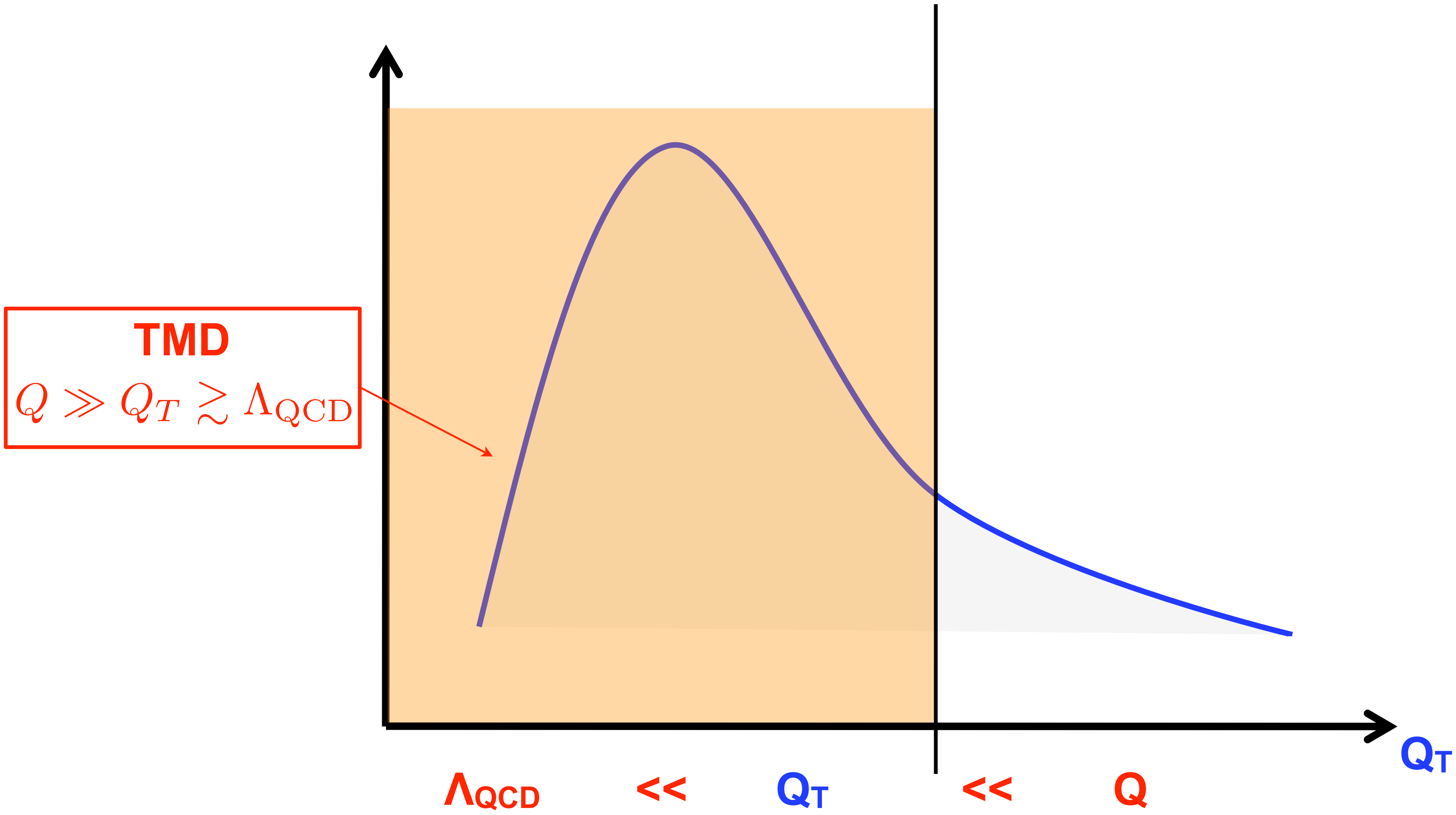

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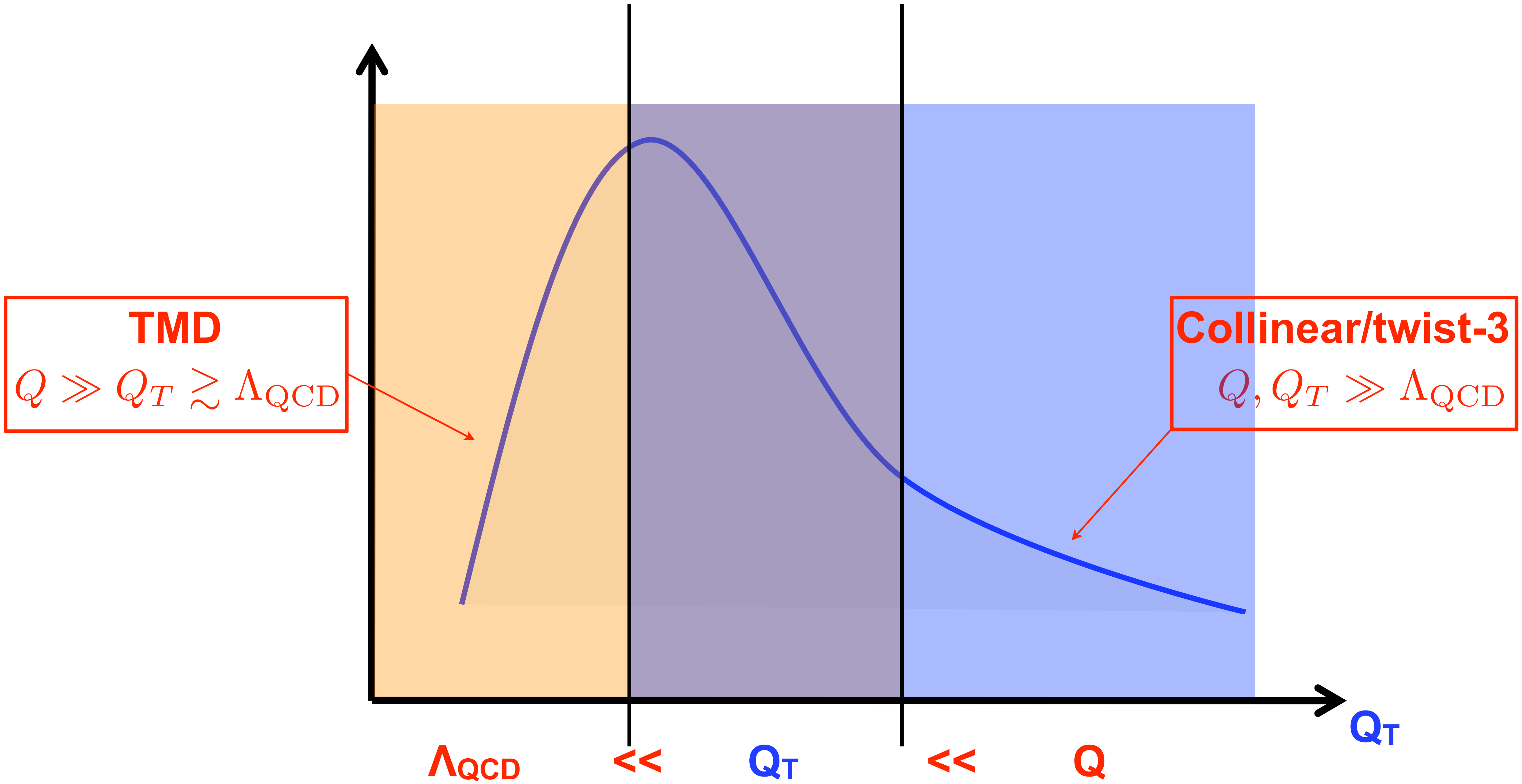

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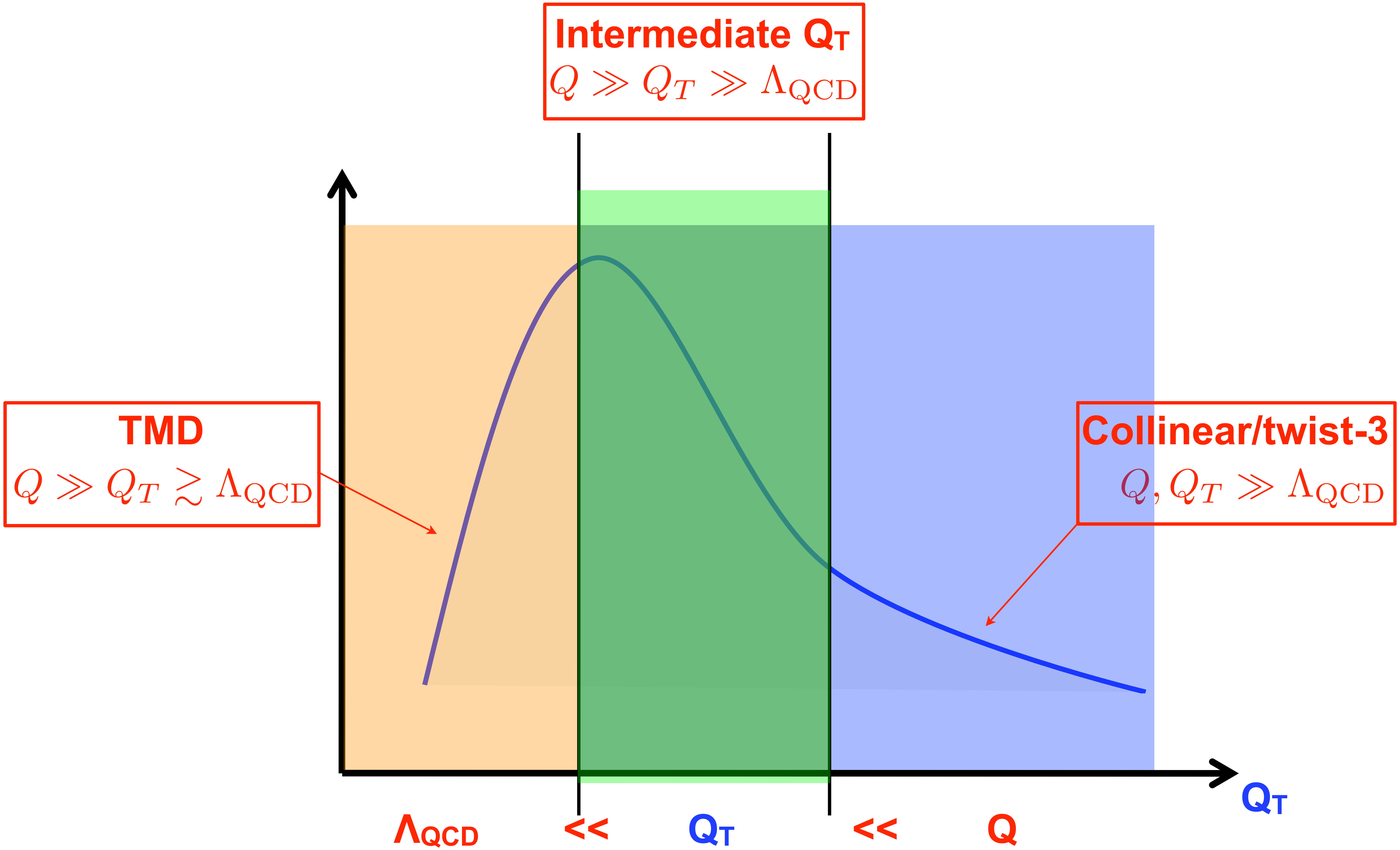


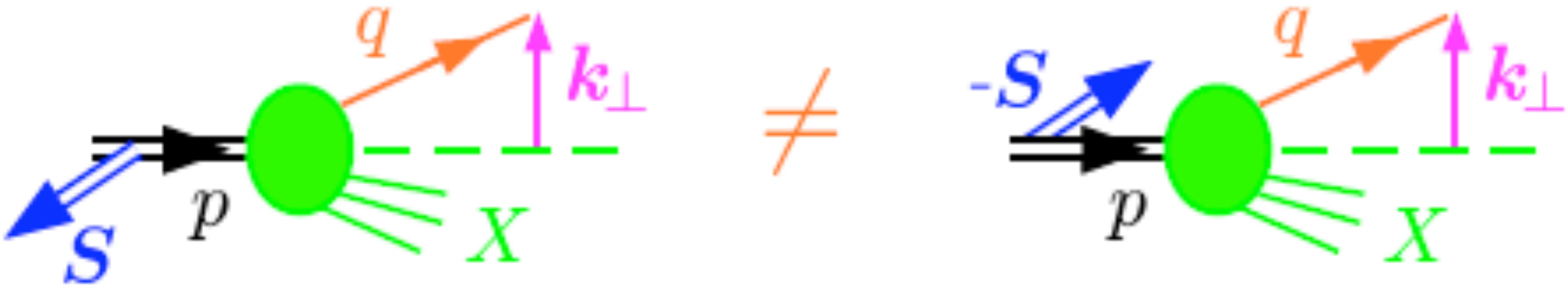
Most discussed example

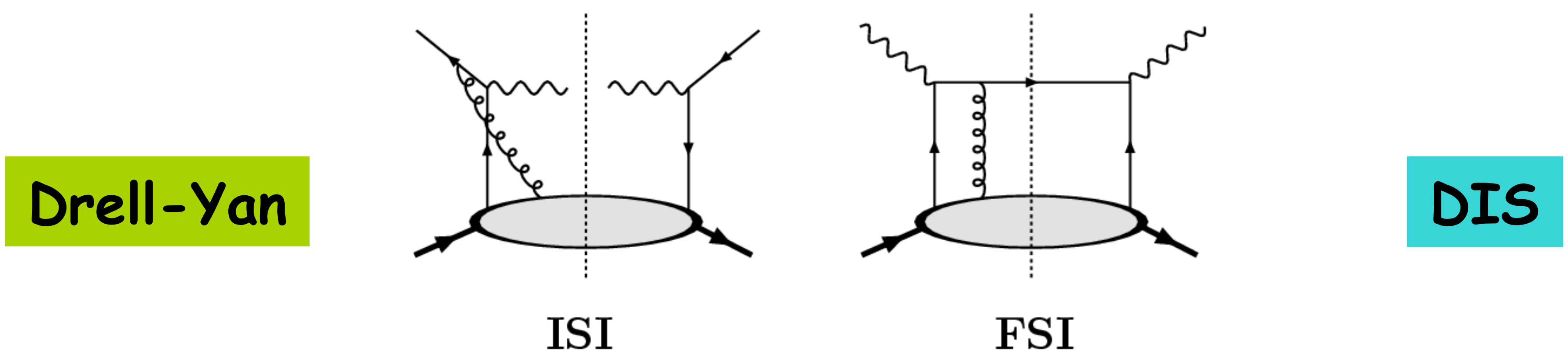
- Sivers function: an asymmetric parton distribution in a polarized hadron (kt correlated with the spin of the hadron)

Spin-dependent

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) \equiv f_{q/h}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/h^\uparrow}(x,k_\perp)\,\vec{S}\cdot\hat{p}\times\hat{\mathbf{k}}_\perp$$

Spin-independent



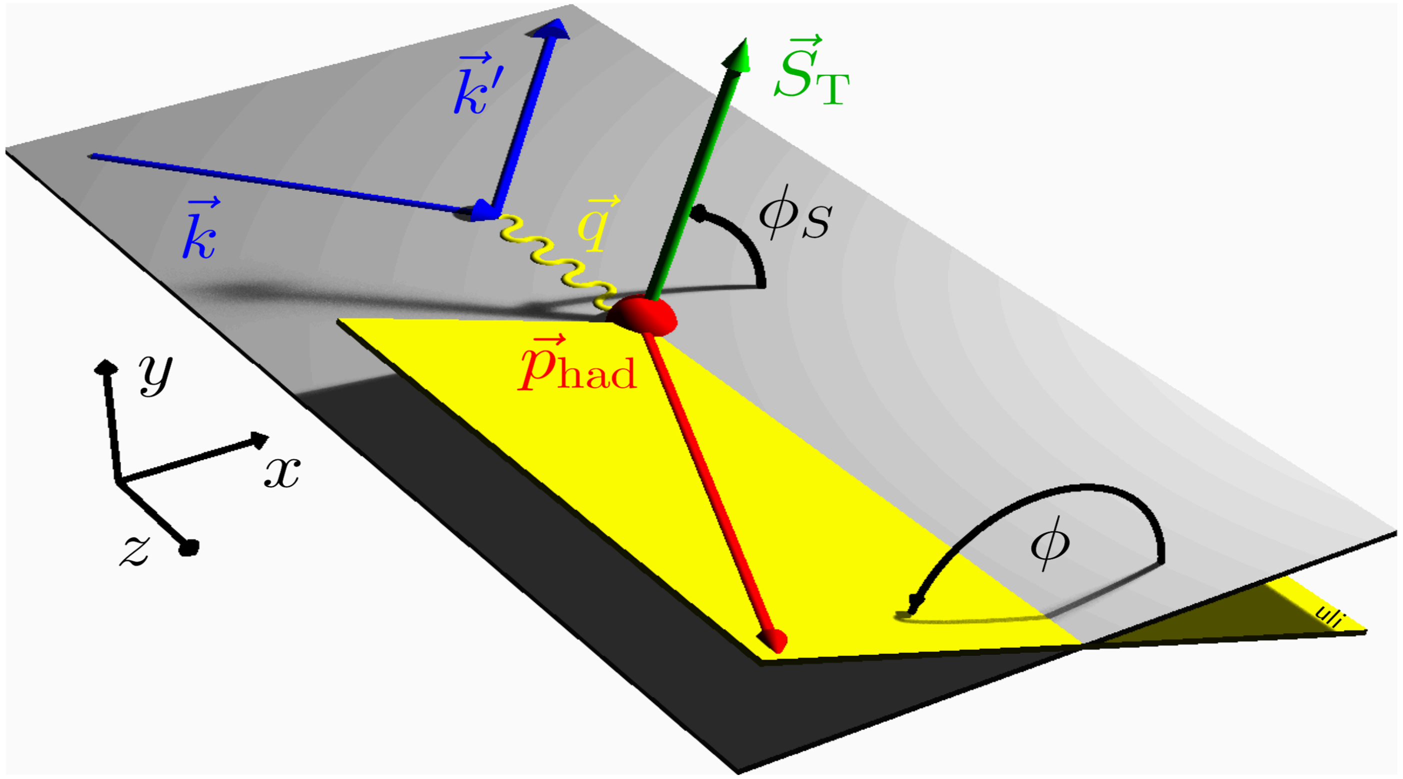


$$\text{Sivers}|_{\text{DY}} = -\text{Sivers}|_{\text{DIS}}$$

Current Sivers function from SIDIS

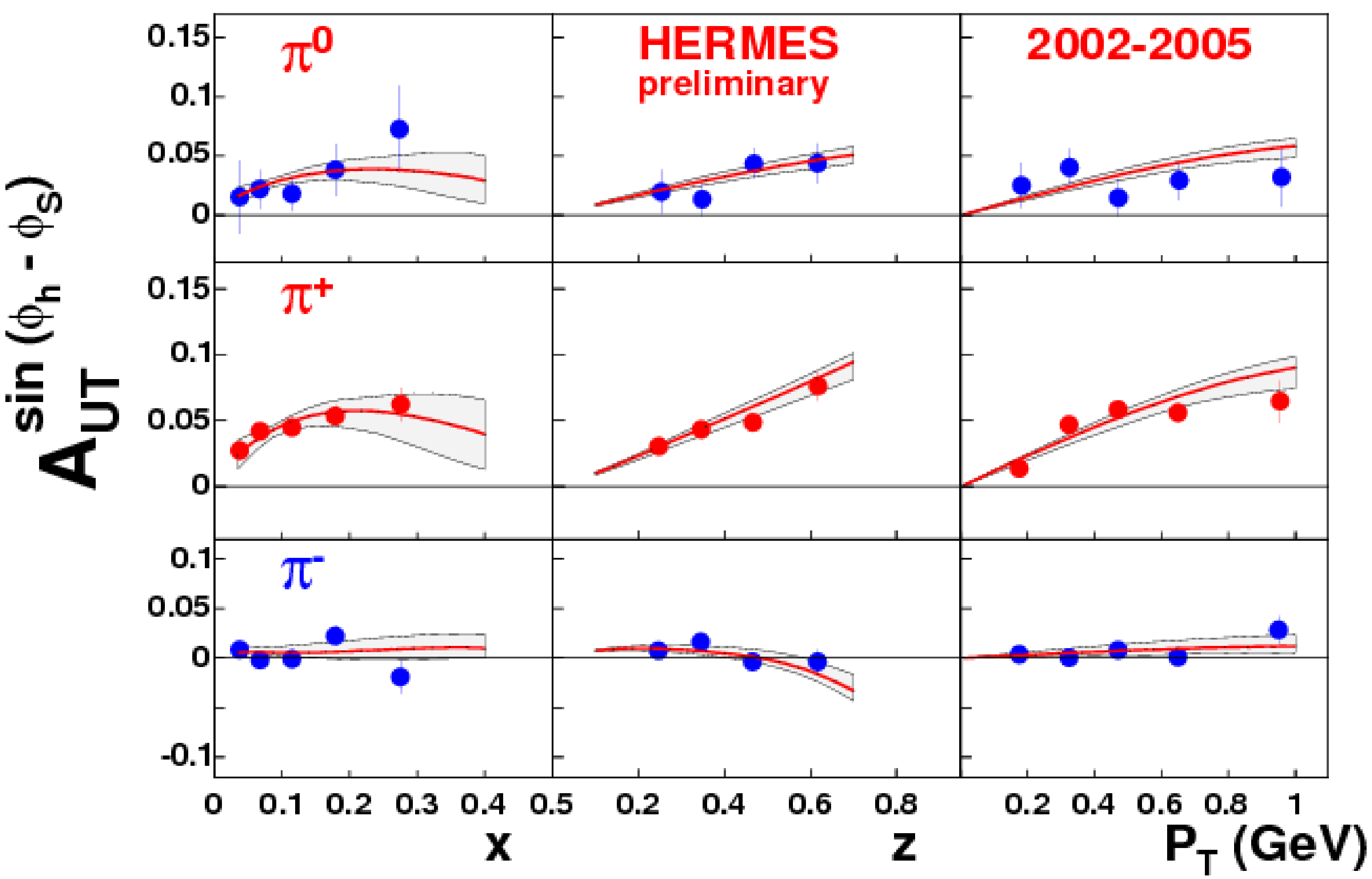
- Sivers and Collins can be separately extracted from SIDIS

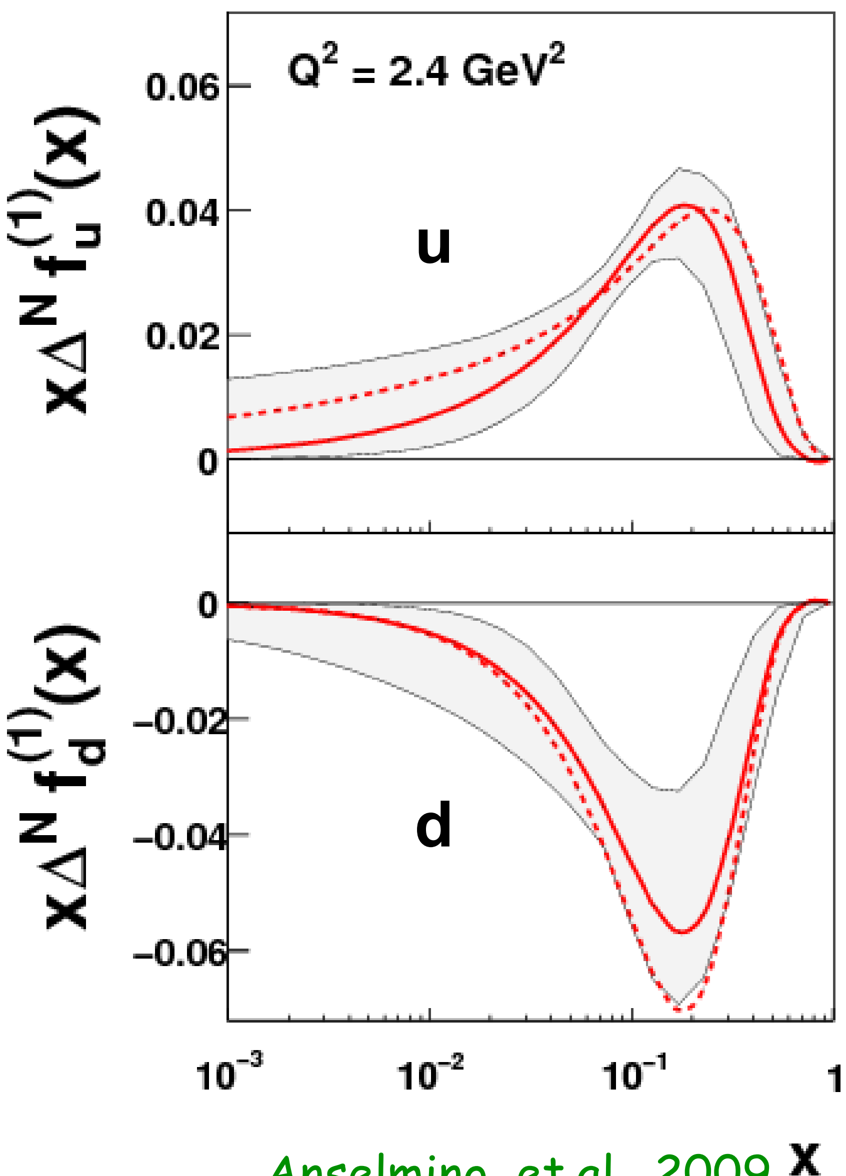
$$\Delta\sigma \propto A_{UT}^{Collins}\sin(\phi+\phi_S) + A_{UT}^{Sivers}\sin(\phi-\phi_S)$$



Sivers function from SIDIS $\ell + p^{\uparrow} \to \ell' + \pi(p_T) + X: \quad p_T \ll Q$

- Extract Sivers function from SIDIS (HERMES&COMPASS)





Anselmino, et.al., 2009

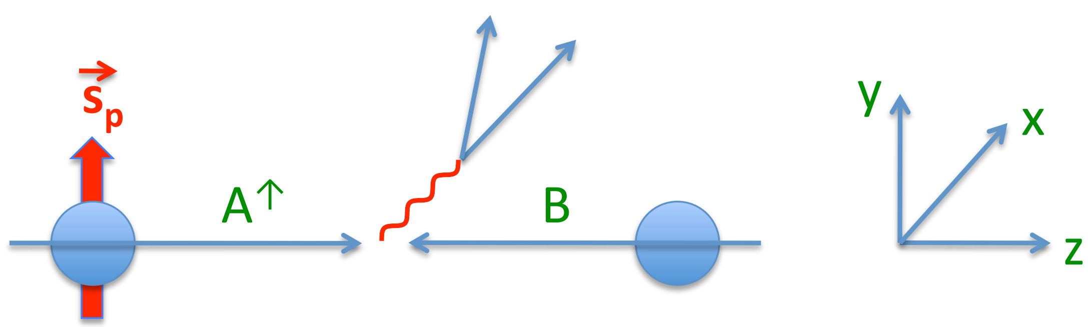
  - u and d almost equal size, different sign
  - d-Sivers is slightly larger

- Still needs DY results to verify the sign change, thus fully understand the mechanism of the SSAs

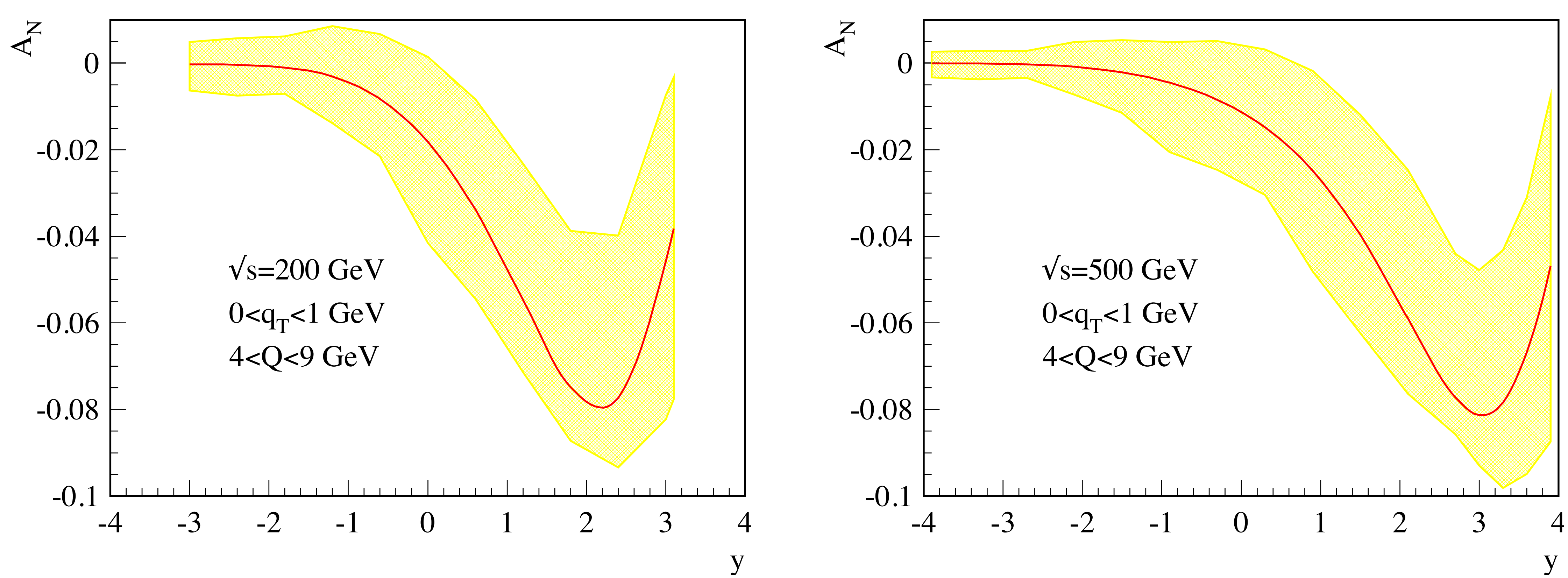
Predictions for Drell-Yan process at RHIC

- Reverse the sign of Sivers from SIDIS and make predictions for Drell-Yan production at RHIC

Kang-Qiu, PRD81, 2010



$$A_N \propto \frac{4}{9}\Delta^N u + \frac{1}{9}\Delta^N d < 0$$



polarized He-3

- Polarized He-3 is mainly a polarized neutron target:
  - polarized He-3: 0.865 n + 2*(-0.027) p
  - unpolarized He-3: n + 2*p
- How the asymmetry will look like

$$A_p \sim \frac{\Delta f_p}{f_p} \qquad\qquad A_n \sim \frac{\Delta f_n}{f_n}$$

$$A_{^3He} \sim \frac{0.865\Delta f_n + 2\cdot(-0.027)\Delta f_p}{f_n + 2 f_p}$$

$$= 0.865 A_n \underbrace{\left(\frac{f_n}{f_n + 2 f_p}\right)}_{\text{dilution factor}} + 2\cdot(-0.027) A_p \underbrace{\left(\frac{f_p}{f_n + 2 f_p}\right)}_{\text{dilution factor}}$$

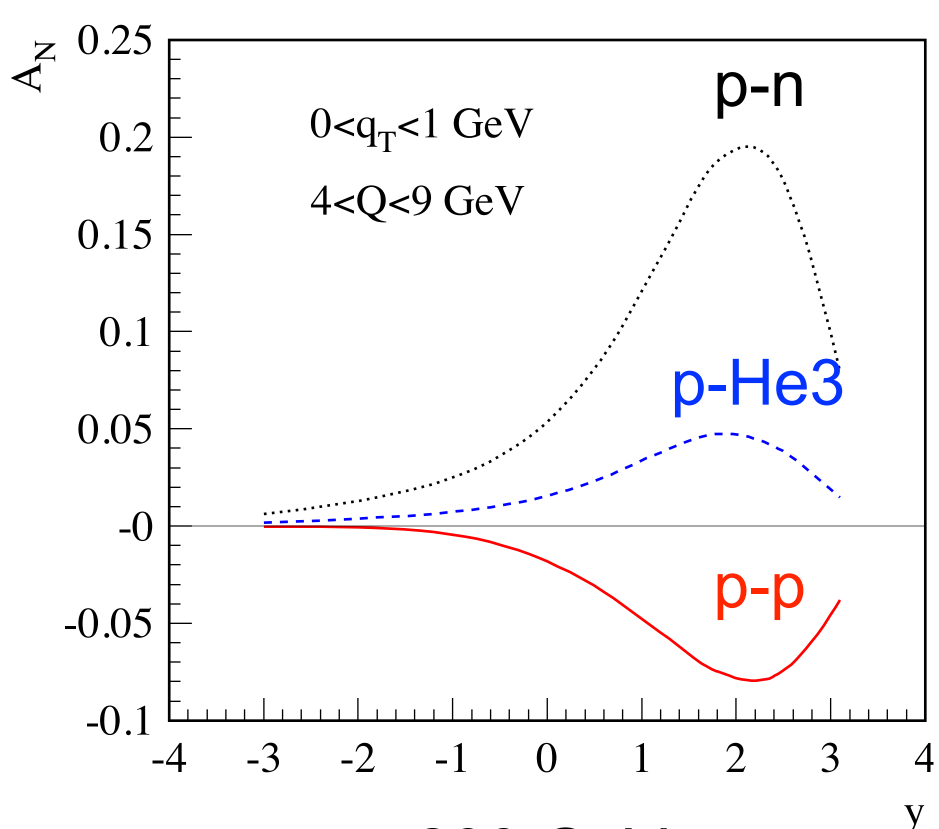
Drell-Yan production for p-p, p-n, p-He3

- Sign will be opposite to the proton case

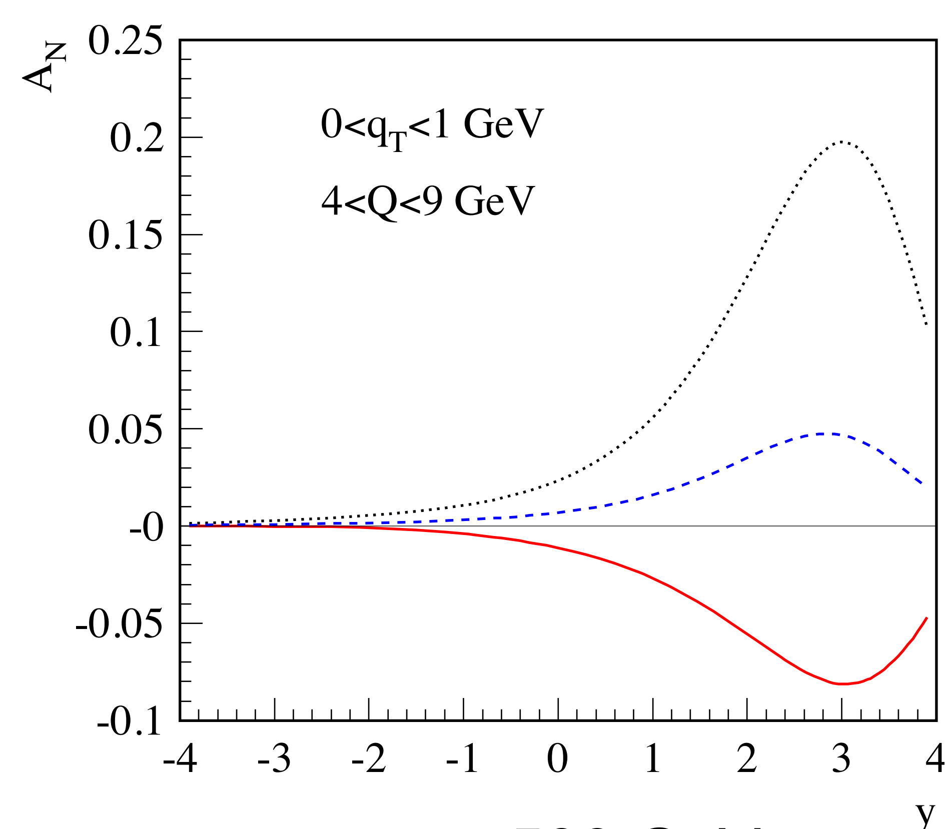
$$A_N = \frac{\sum_q e_q^2 \int \Delta^N f_{q/A^\uparrow}(x_1, \mathbf{k}_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})}{2\sum_q e_q^2 \int f_{q/A}(x_1, k_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})} \propto \frac{4}{9}\Delta^N u_{\text{neutron}} + \frac{1}{9}\Delta^N d_{\text{neutron}}$$

$$= \frac{4}{9}\Delta^N d_{\text{proton}} + \frac{1}{9}\Delta^N u_{\text{proton}}$$

  - d-Sivers is positive, $A_N>0$
  - d-Sivers is slightly larger, at the same time, it gets enhanced more by 4/9 compared with u-Sivers, thus the size of the asymmetry will be much bigger than the proton case



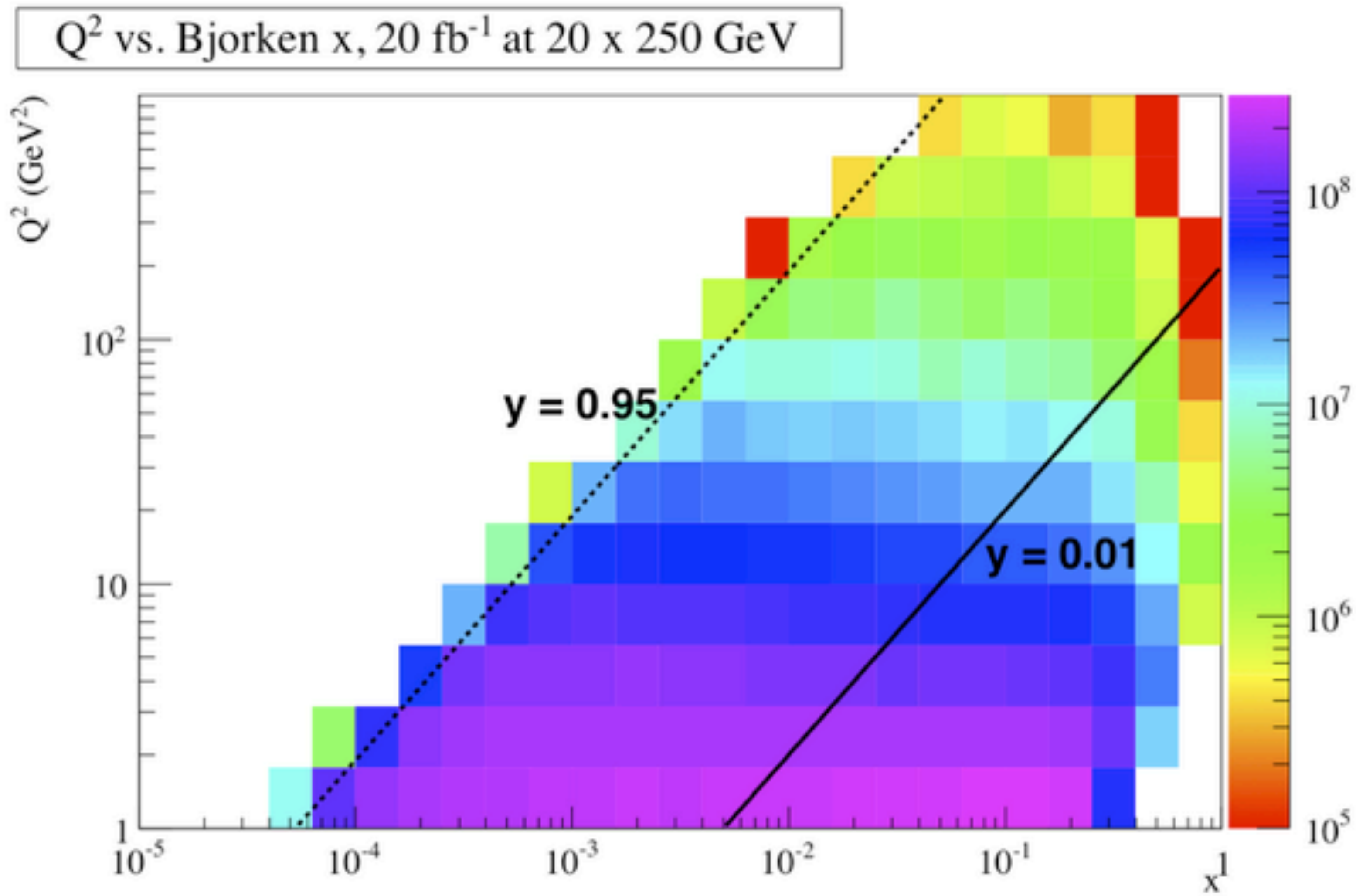
200 GeV



500 GeV

Future EIC

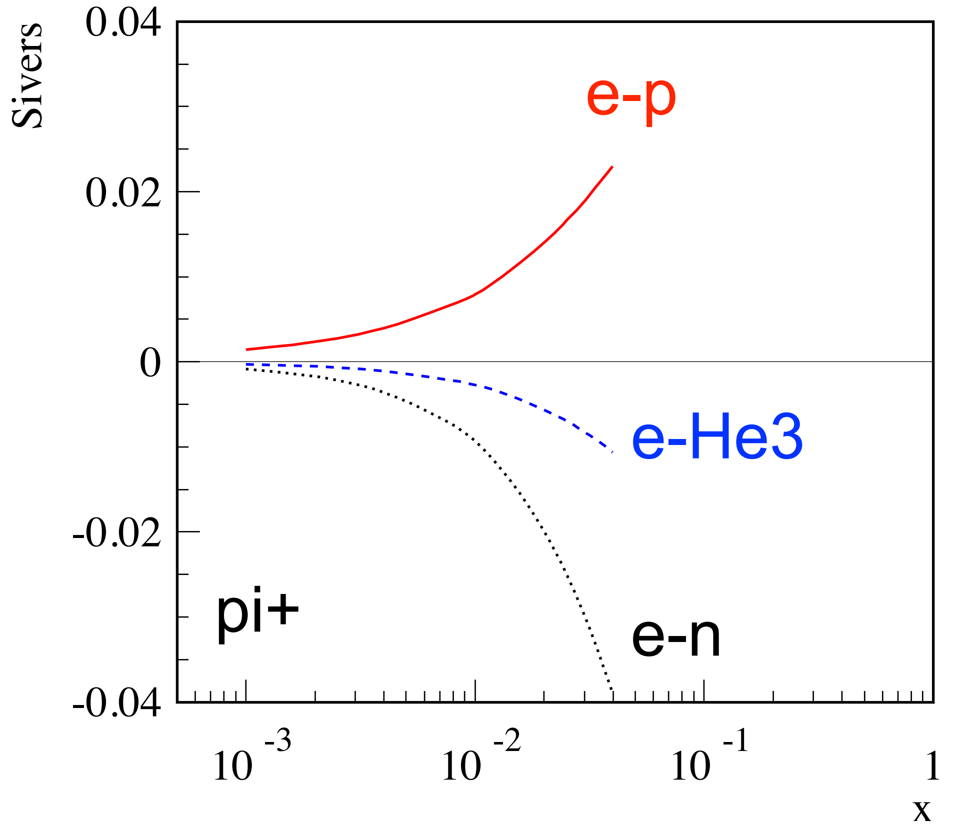
- Choose 20 GeV electron on 250 GeV proton
  - Q^2=10 GeV^2
  - 0.01<y<0.95

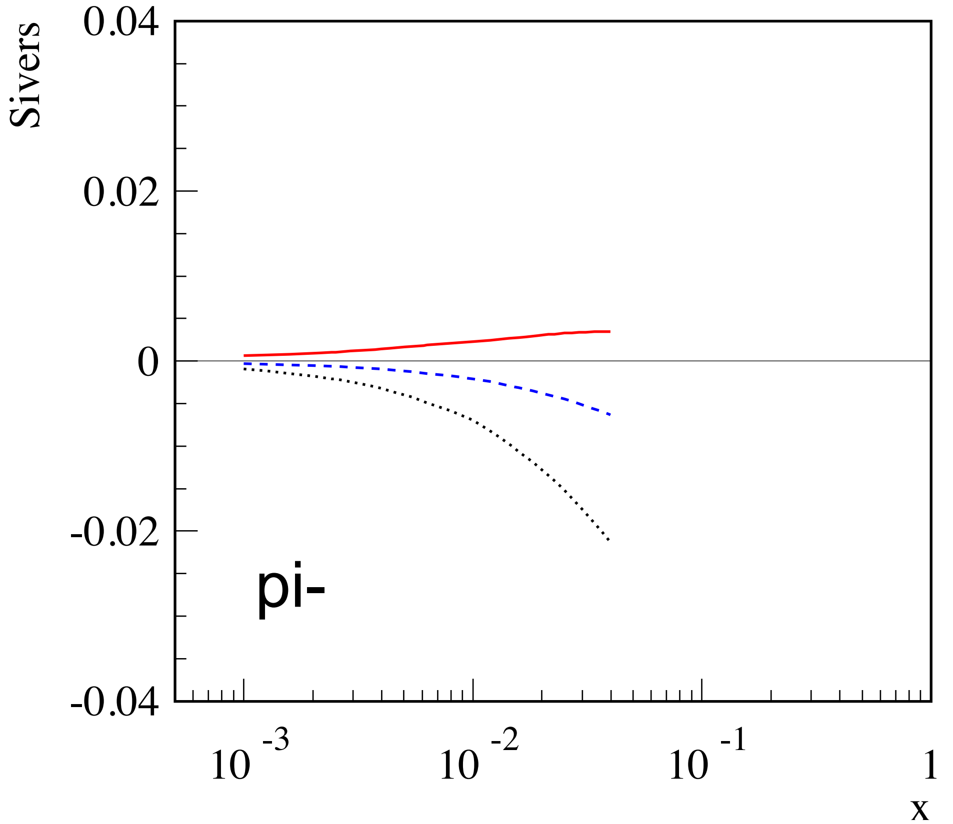


Future EIC

- Integrated for 0.4<z<0.6, and 0<pt<1 GeV

$$A_N^{\sin(\phi_h-\phi_s)} \sim \frac{4}{9}\Delta^N u \cdot u \cdot D_u + \frac{1}{9}\Delta^N d \cdot d \cdot D_d$$





  - Need a bit caution: Sivers function is only constrained at x~[0.1,0.3], EIC is mainly sensitive to low x region

- Some Collins estimate, see 1101.5196 (She and Ma)

Hadron production at RHIC

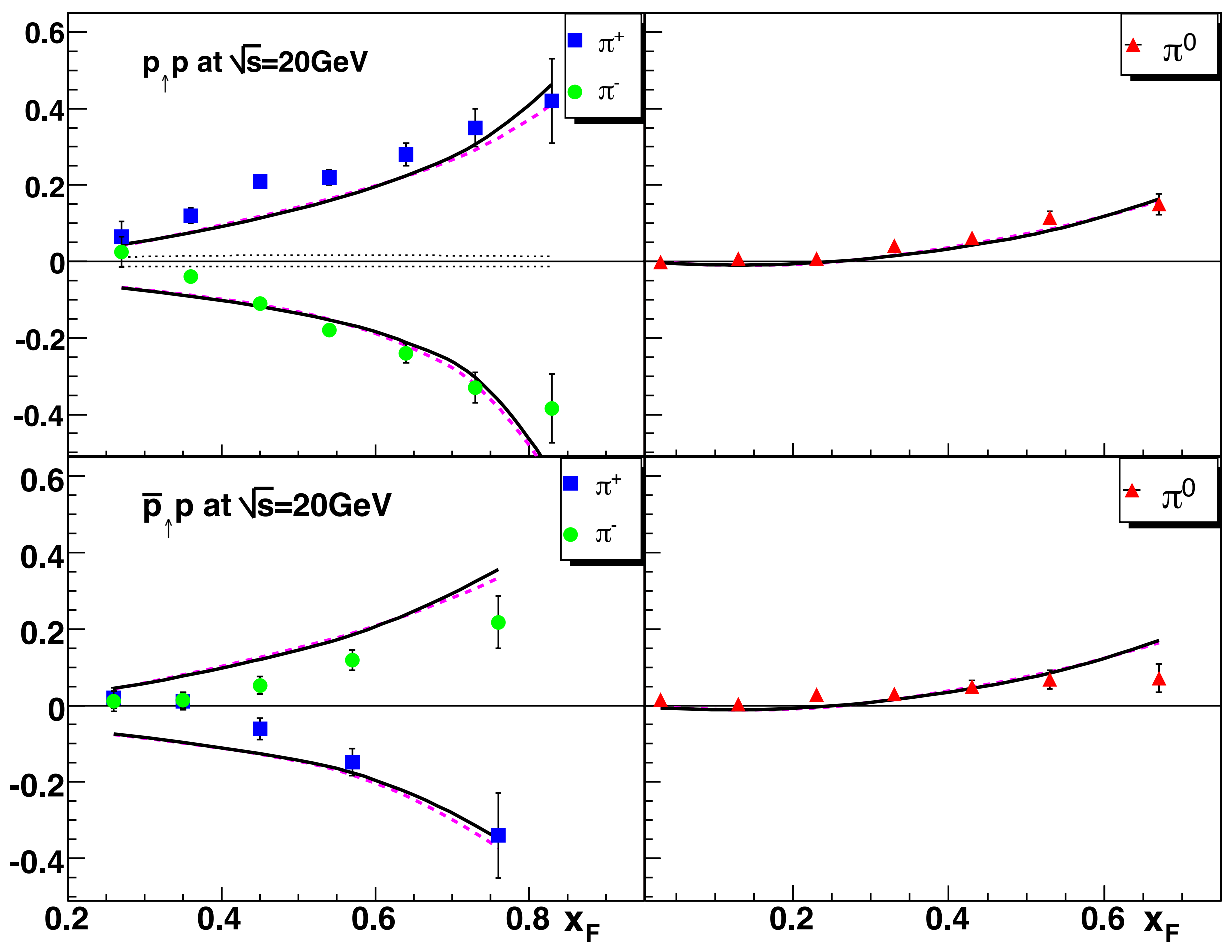
- Have the most data by far, but it is least understood
  - Sign mismatch — Kang-Qiu-Vogelsang-Yuan, 2011
  - A complete picture consistent with all the available data (DIS, pp) is still not available — Kang-Prokudin, still working …
- With this in mind, we will still use the parametrization from year 2006. In the sense, it is at least consistent. Also the prediction should be reasonable — Kouvaris-Qiu-Vogelsang-Yuan, 2006

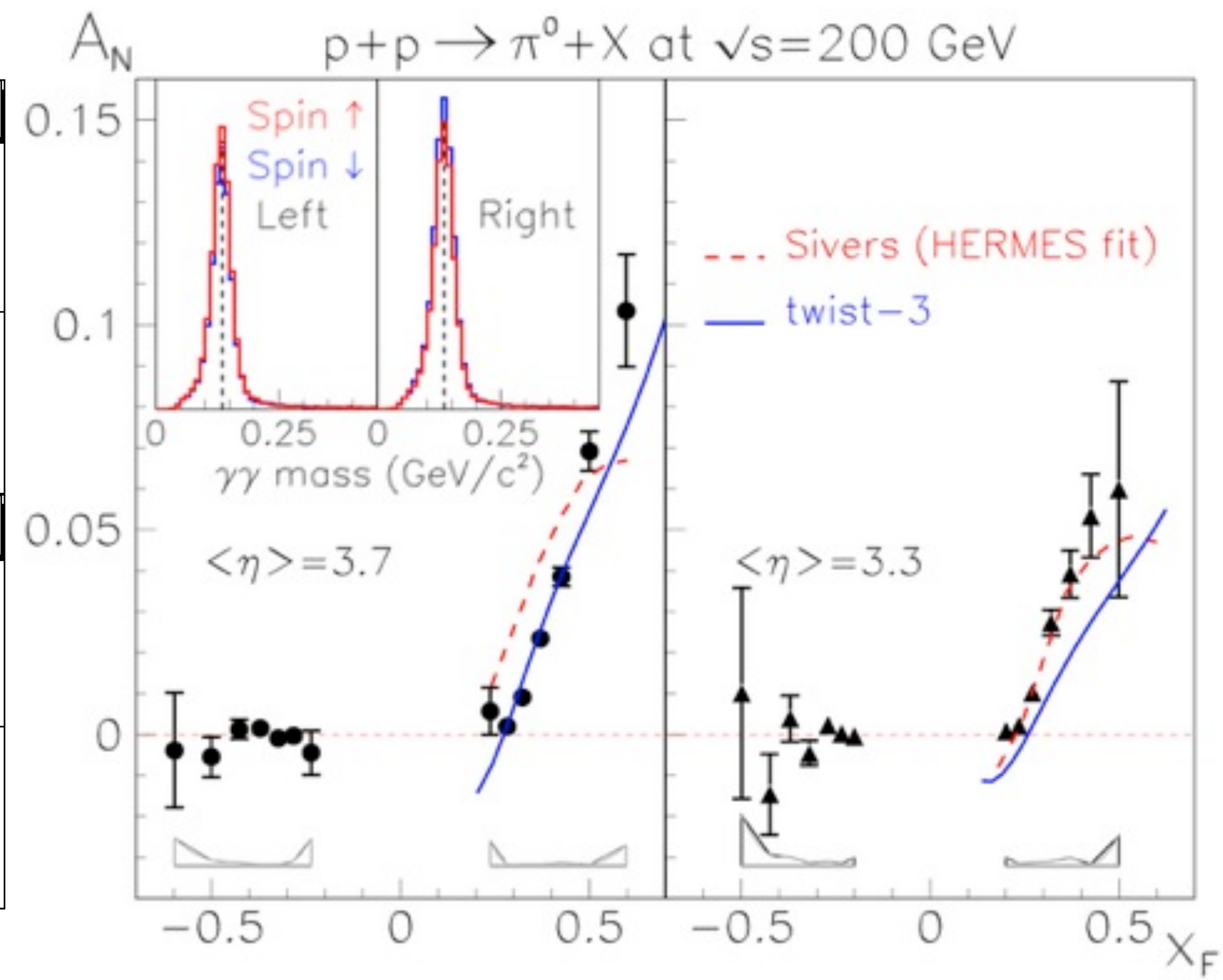
Initial success of twist-3 approach

- Describe both fixed-target and RHIC well: a fit

$$T_{q,F}(x,x) = N_q x^{\alpha_q}(1-x)^{\beta_q}\phi_q(x)$$

Kouvaris-Qiu-Vogelsang-Yuan, 2006

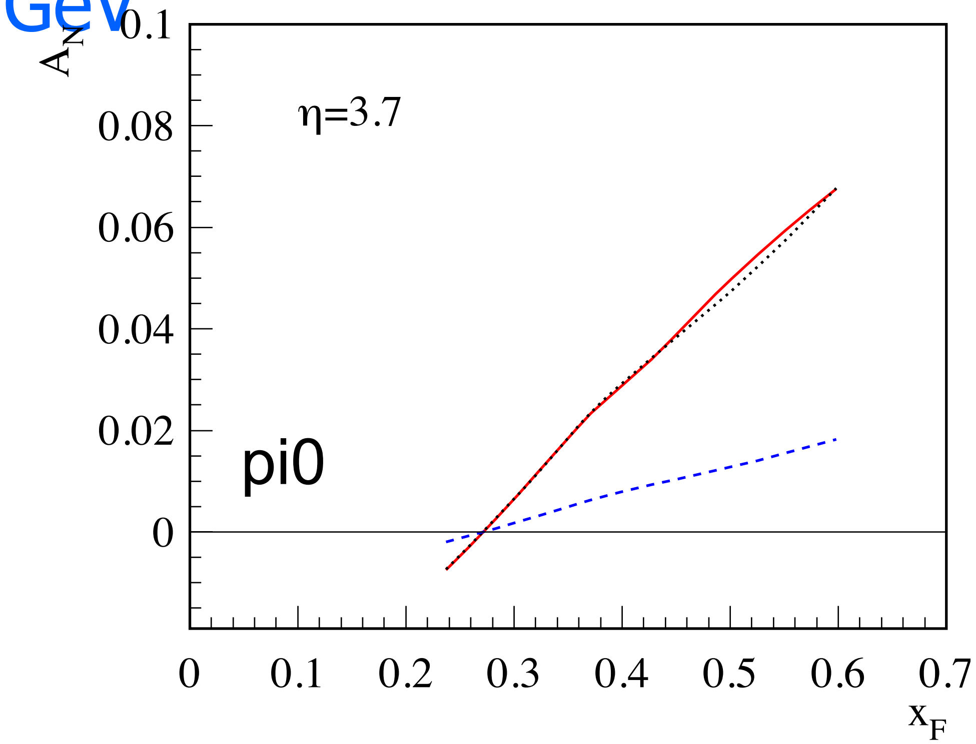


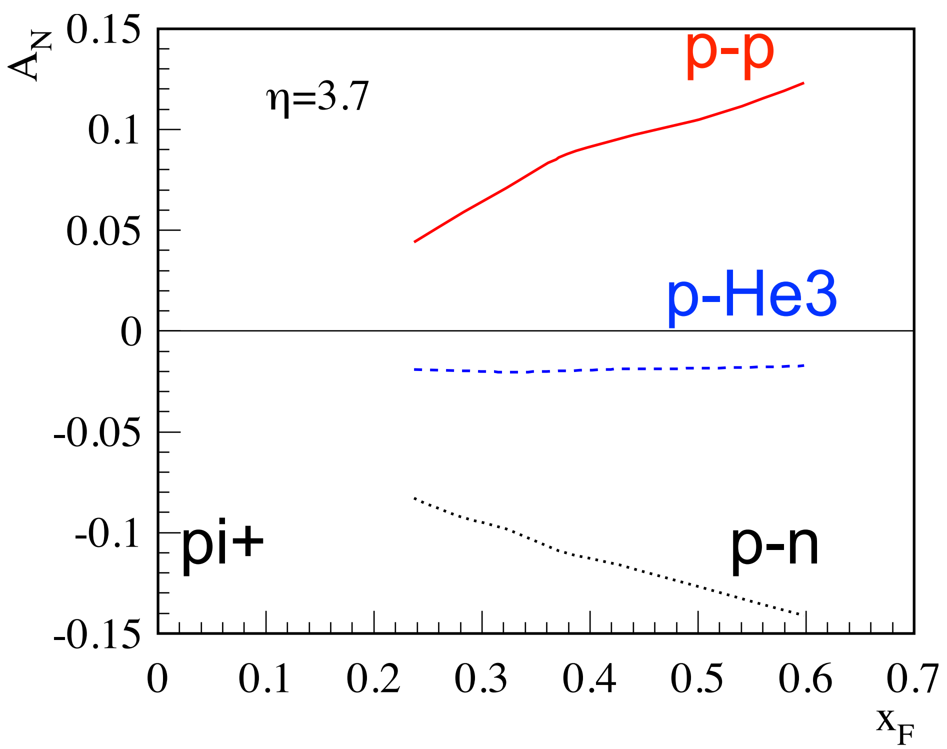


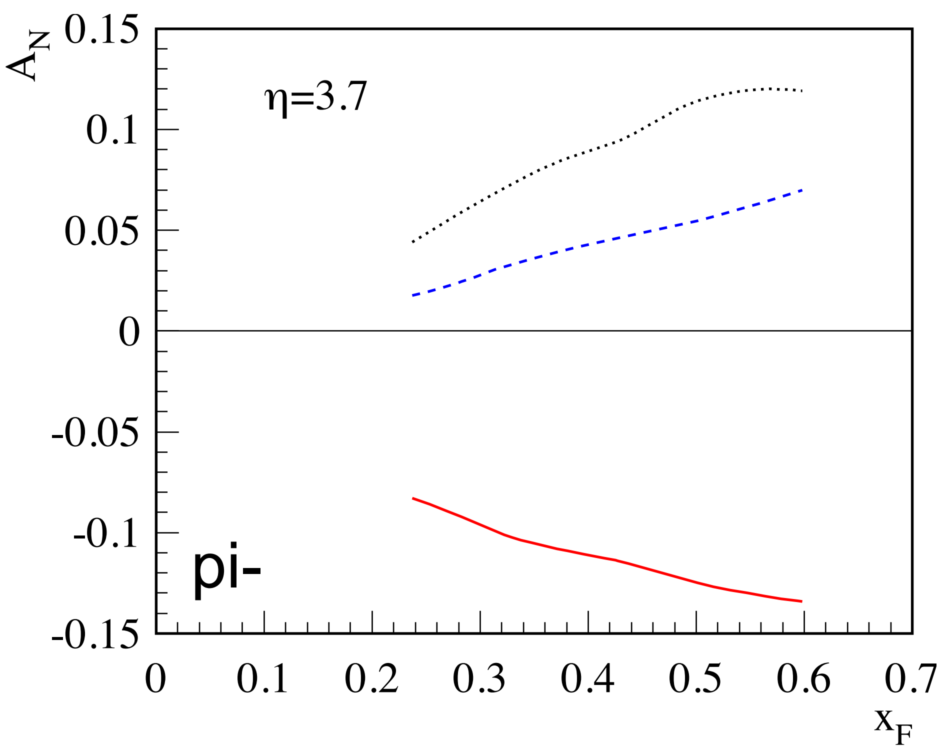
$$p^\uparrow p \to \pi + X$$

Single pion production

- CM energy 200 GeV







Summary

- Spin is a useful tool to probe hadron structure
- Spin-dependent distribution, Sivers function has opposite sign for u and d quark flavor
- Polarized He-3 could be used to confirm and verify this opposite sign
- If one could tag neutron, it typically leads to larger asymmetries
- Still need more data to establish the theory for the transverse spin phenomena: single inclusive jet, direct photon, Drell-Yan

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Thank you